What is the Nature of Hot Nuclear Matter?
Exploring QCD at High Energy Density

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Introduction

One of the fundamental tasks of modern Nuclear Physics is the understanding of the structure of the vacuum, and the long distance behavior of the strong interaction. Quantum Chromodynamics (QCD) is the present theory of the strong interaction in the context of the Standard Model of particle physics. However many of the primary features of our universe are not easily understood from the form and symmetries of the Standard Model. A rather startling view of the vacuum arises when one examines the long distance behavior of QCD. The vacuum - rather than being empty – is composed of a quark condensate that fills all of space, breaking the symmetries of the Standard model and giving rise to a variety of phenomena: the confinement of quarks into hadrons, the binding of nucleons in the nucleus, and the large mass of the hadrons as compared to the light quarks. It is a remarkable fact that a proton, made of primarily 3 light quarks weighs about 300 times the mass of a bare quark - the majority of the mass of a proton comes from its coupling to the quark condensate which comprises the QCD vacuum.

One is then immediately led to ask whether this vacuum structure can be experimentally altered changing its characteristics and perhaps revealing the underlying symmetries of the Standard Model. Lattice QCD calculations have shown that this is possible, The underlying (chiral) symmetries of the Standard Model should be restored when the vacuum condensates melt at temperatures exceeding 170 MeV. At these temperatures matter should behave as a plasma of nearly massless quarks and gluons, known as the quark-gluon plasma (QGP), a state existing in the first microseconds after the big bang.

The vacuum, and in fact any system of quarks and gluons, will have a complex phase structure; similar to that of many other bulk materials such as ordinary water, which exhibits the well-known phases of solid, liquid, and gas and accompanying phase transitions. The QCD phase diagram is shown in figure 1. The phase structure of the vacuum state is along the vertical axis. Two manifestations of the phase transition are thought to exist. The first is that of deconfinement, in which the quarks and gluons become free of the their bondage into protons and mesons. The second is that of chiral symmetry restoration in which the masses of the quarks are reduced to their bare quark values. If the temperature were above the chiral phase transition temperature then the proton, for example, would be very light, of the order of a few MeV characteristic of the light quark masses. It is still an open question as to whether these two phenomena happen under exactly the same conditions of pressure and temperature.

In recent years, theorists have made major advances in the understanding of cold quark matter at high density, at the far right of figure 1. In this very dense but very cold environment quark matter displays many characteristics more familiar to a condensed matter physicist than to a plasma physicist: Cooper pairs form, and the quark matter becomes a color superconductor, characterized by Meissner effects and gaps at the quark Fermi surfaces. Cold quark matter may exist in the centers of neutron stars and we can hope that it will become possible to use astrophysical observations of neutron star phenomena to learn whether or not they feature quark matter cores. Ultimately, we must fit together the picture of cold dense quark matter gained from astrophysical observation with the picture of hot quark-gluon plasma that we hope to gain from experiments at RHIC into a coherent, unified phase diagram for QCD.

The heavy ion program at RHIC ushers in a new era for studies of the most basic interactions predicted by QCD in bulk nuclear matter at temperatures and densities great enough to excite the expected phase transition to a quark-gluon plasma. As this program matures, experiments at RHIC will provide a unique window for detailed studies of the hot QCD vacuum, with opportunities for fundamental advances in the understanding of quark confinement, chiral symmetry breaking, and, very possibly, new and unexpected phenomena in the realm nuclear matter at the highest density.

In concert with these studies, the RHIC spin program is expected to carry out decisive measurements of the spin structure of the nucleon. In an experimental program that is completely integrated and compatible with the heavy ion experiments, the capability to study polarized proton collisions at collider energies will allow the proton spin structure to be studied with perturbative QCD probes—allowing the collisions to be interpreted unambiguously as interactions of polarized quarks and gluons. Specifically, these studies should give direct measurements of the contribution of gluons and sea quarks to the spin of the proton, results that are not accessible to deep inelastic lepton scattering experiments.

By colliding heavy ions at extreme energies, mesoscopic regions of sufficient energy are created with conditions favorable for melting the normal vacuum and creating this novel state of matter. With the unique ability to collide beams of ions from protons to gold, and with center of mass energies from 20 to 100 GeV per nucleon, RHIC addresses a number of fundamental questions:

What are the properties of QCD vacuum and its connection to the masses of the hadrons? What is the origin of chiral symmetry breaking?

Can we locate signatures of the deconfinement phase transition as the hot matter cools? What is the origin of confinement?

What are the properties of matter at the highest energy densities? Is the basic idea that this is best described using fundamental quarks and gluons correct?

In experiments that can be done in the laboratory, how do the created systems evolve? Does the matter approach thermal equilibrium and what are the initial temperatures achieved?

The US has the premier laboratory in which to study these questions. It is likely that an initial understanding of high density QCD matter and its associated phase transitions will be achieved in the next 5 years, however there will still be a great deal to be done subsequent to the initial discoveries. Indeed, water, ice and steam have been known to humans for many thousands of years, but scientists are still using modern techniques to discover new properties and phases of water. Similarly, it is clear, that expanded facilities will be necessary in the outlying years of this long range plan to get a detailed description of hot nuclear matter.

Achievements Since the Last Long Range Plan

The US program in Relativistic Heavy Ion Physics has a long history, starting with work at the Bevalac and continuing to the AGS, with a large contingent of the US community participating in the CERN program. A new frontier has begun with the initiation of the RHIC program giving us an increase in center of mass energy of almost an order of magnitude. It is important to understand that the fixed target at the AGS and CERN on one hand, and collider experiments at RHIC and the LHC are studying rather different regimes on the QCD phase diagram as shown in figure 1 The fixed target experiments have studied systems of high baryon density. At CERN, a somewhat lower baryon density but higher energy density was observed than at the AGS. In contrast, heavy ion collisions at RHIC and the LHC take us into the regime where the net baryon density of the system is very low. This situation is of course, particular interesting because it is, essentially, a high temperature vacuum. In addition, theoretical calculations, both analytical and lattice gauge calculations have improved – lattice calculations have enabled theoreticians to calculate, with more certainty, the location of the phase transition.

AGS and CERN programs

QCD has yielded its secrets up slowly. Even in the perturbative regime, the physics community did not immediately accept experimental evidence for gluons. A number of expected signals of quark gluon plasma formation have been observed in fixed target experiments at CERN (and some at the AGS), but the evidence is not yet unambiguous. Some of the most important of the results from CERN and the AGS are reviewed here. A more complete review can be found in Nuclear Physics: The Core of Matter, the Fuel of Stars. (by the Committee on Nuclear Physics, National Research Council, National Academy Press, 1999) Studies of particle abundances and spectra, as well as Bose-Einstein correlations, which give information about the space-time evolution of the collision, from the AGS and CERN indicate that the system undergoes a state of rapid expansion and is close to both chemical and thermal equilibrium. Thermal equilibrium is thought to be reached very rapidly, but standard hadronic cross sections have difficulty accounting for the rapid rate at which this thermalization occurs. However, interaction cross sections arising from color among quarks are larger and could drive rapid thermalization.

A state of free quarks is expected to show a strong enhancement of strangeness, particularly of anti-strange particles, whose yield would ordinarily be kinematically suppressed by their relatively large masses. Experiments at CERN, in particular WA97 see enhanced strange anti-baryon production, with increasing enhancement for each additional unit of strangeness. Experiments at the AGS, which have been able to detect only the $\bar{\Lambda}$, see a very strong enhancement in the $\bar{\Lambda}$ to $\bar{p}$ ratio. Thus far, standard hadronic models cannot reproduce these results.

In 1986, Matsui and Satz suggested charmonium as a probe of the hot medium created in relativistic heavy ion collisions. A colored medium (i.e. a deconfined one) would break up a $c\bar{c}$ quark pair created by hard nucleon-nucleon scatterings, thereby causing the charmonium state to "melt". This depends on the energy density of the medium and the species of charmonium being considered, with the less tightly bound χ and ψ' states breaking up at lower energy densities than the J/ψ. Just such a phenomenon was observed by NA50. Theoretical and experimental work was required to separate initial state effects on charmonium formation, final state breakup by ordinary hadronic matter (as observed in p-nucleus collisions, for example) and the medium effects of interest.

J/ψ suppression signals deconfinement. Signatures that may be interpreted as evidence of chiral symmetry restoration were also seen. NA45 observed an excess in electron pair yields at invariant masses between 200 and 800 MeV which can be explained as a broadening and mass shift of the ρ meson due to the onset of chiral symmetry restoration. Competing interpretations of the data as arising from thermal radiation are also possible.

The fixed target experiments have certainly proven that heavy ion collisions create high energy and baryon densities. The density of hadrons is so large, that there is simply not enough room for them to co-exist as a superposition of vacuum state hadrons. The observed signatures are not readily explainable by standard hadronic models. It is also clear that a great deal remains to be done in the CERN/AGS energy regime. A new experiment (NA60) is now under construction at CERN to measure the charm production cross-section, necessary to resolve questions in interpretation of the dilepton results. Other laboratories in Japan and Germany are contemplating construction of to further these studies as well. Systematic understanding of the signals, by varying the beam energy for example, were hampered by the fact relativistic heavy ion work at both CERN and the AGS shared running time with other programs. One of the critical lessons for the Relativistic Heavy Ion community in the US is that a commitment to a thorough study using a dedicated machine is imperative. A systematic measurement of multiple signatures in p-p, p-nucleus and nucleus-nucleus collisions is a prerequisite to a clear and unambiguous physics conclusion.

First glimpses from the initial run of RHIC

The Relativistic Heavy Ion Collider, RHIC, which began construction in 1991, was completed and commissioned in the summer of 2000. The first data taking run lasted for 3 months, during which the machine reached 10% of design luminosity at 130 GeV/nucleon center of mass energy in Au-Au collisions. A successful commissioning of polarized protons was also done with protons in one ring of RHIC. A second run of the collider started in June of 2001 and will complete in early 2002 in which it is expected that the machine will reach full the full design luminosity of $2x10^{26}$ $cm^{-2}s^{-1}$ at an energy 200 GeV/nucleon in the center of mass for Au ions. The first of the polarized proton runs will take place during this run. The detectors, which were only partially instrumented for the first run, are substantially complete. All were equipped with identical zero-degree calorimeters for to determine the impact parameter, or centrality, of the collision and allow selection of identical classes of events in all four detectors. The detectors are shown in figure 3.

In the 2000 run, about 10M events were collected between the 4 detectors with RHIC operating at 65GeV per nucleon, allowing for a good start on the physics program. About 2 orders of magnitude more events are expected in 2001.Analysis of the data has taken place in a timely fashion, and already much has been learned about heavy ion collisions at RHIC energies. What follows is a sample of the most important results as of the writing of this document.

The particle density in central gold-gold collisions in the hottest mid rapidity region, per participating beam nucleon, is about 70% higher than at CERN (PHOBOS, PHENIX, STAR). This means that already at 65% of RHIC's design energy, the created energy density is at least 70% higher than previously attained at CERN. In the most violent collisions more than 6000 particles are produced (PHOBOS), and for the first time in heavy ion collisions a clear central plateau is seen (PHOBOS, STAR), yielding important information on the space-time aspects of the collision and particle production process. Furthermore the yield per participant increases with centrality (PHENIX, PHOBOS) indicating the importance of multiple collisions and hard processes (figure 4). A measurement of the transverse energy distribution by the PHENIX collaboration shows a similar behavior. Depending on the thermalization time, the data imply that the energy density is considerably higher at RHIC than at CERN.

The azimuthal asymmetry of particle production in peripheral and semi-central collisions, known as elliptic flow, is found to be surprisingly large as shown in figure 5 (STAR, PHOBOS, PHENIX). This is interpreted as evidence that a high degree of thermalization takes place early in the collision and that there is built up of high pressure. Is simple terms, it appears that there is an enormous build up of pressure early in the collision, followed by a violent explosion.

At central rapidity the baryon to antibaryon ratio approaches unity (STAR, BRAHMS, PHOBOS, PHENIX) indicating that the quantum numbers of the hot system are approaching that of the vacuum. Bose-Einstein correlation studies have yielded size parameters of approximately 6 fm (STAR), surprisingly similar to that measured at CERN.

One of the most intriguing results comes from a measurement of the neutral pion pt spectrum. High pt particles are expected to be leading particles from quark and gluon jet fragmentation. A fast moving colored parton (quark of gluon) is an ideal probe of hot nuclear matter. In normal nuclear matter, a quark would experience only a small amount of energy loss; hence a jet would essentially carry the energy imparted to the original struck parton. In a quark gluon plasma, the deconfined color fields would slow the quark down considerably ~ energy losses can be as much as 10 GeV/fm. High pt particles would be strongly suppressed in nucleus – nucleus collisions in which a QGP were formed in comparison to a pp collisions. Figure 6 shows a ratio between π^0's measured in central Au-Au collisions in PHENIX and π^0's in pp collisions scaled by the number of binary collisions. The ratio is significantly less than one. The usual nuclear "Cronin" effect is expected to enhance this ratio above one. Whether this is a definitive signal of a QGP is yet to be determined. Future data will give more statistics and higher pt, as well as proton nucleus data for comparison.

The interpretation of all these facts in terms of the temperature, entropy production, and ultimately on the existence of a phase transition will take some time. Early results on charmonium suppression, dilepton spectra, and multi-strange anti-baryons will require data to be taken during the 2001-2002 year. In any case this has been a spectacular beginning for the RHIC experiments.

Scientific Opportunities

The First 5 years

The Relativistic Heavy Ion Collider has just begun its task of uncovering the secrets of QCD. Detectors have been completed only recently, and the second run is underway. The next five years should yield a wealth of new information. In order to realize this promise it is critical that *the highest priority is to utilize RHIC to its fullest potential. Sufficient running time is required to realize the physics promise of RHIC and reap the rewards of our investment in RHIC's construction. Certain short-term upgrades will be necessary as well as R and D for major upgrades to the machine luminosity and to the detectors.*

Full utilization of RHIC in terms of running time is imperative over the next 5 years. This will allow collection of a large set of both heavy and light ion collisions for accurate measurement of low cross section phenomena, such as multi-strange baryon spectra, J/ψ yields, and jet production. Establishing the existence of a phase transition from hadrons to deconfined plasma requires systematic scans in collision energy and beam particle to vary the initial temperature and system size. For each beam combination and energy a high quality measurement of the potential plasma signatures must be made, necessitating 5-10 weeks of running for each case. RHIC must measure those probes of the hot medium which have produced the intriguing yet inconclusive results at CERN; many of these have small production cross sections, e.g. J/ψ and jets, so long runs will be required.

Unambiguous establishment of new physics also will rely upon "control" measurements of the same observables in elementary nucleon-nucleon collisions and in cold nuclear matter, studied via proton-nucleus collisions, at the same energy in the same detectors.

High quality measurement of spin observables, such as ΔG, the fraction of the nucleon's spin carried by the gluons, requires polarized proton-proton collisions for at least 10 weeks per year over multiple years. Similar requirements on p-p and p-A running follow from the requirement that the measurements of rare processes in these reactions be of sufficient statistical accuracy to serve as comparison data sets for the heavy ion program. In addition to the all-important systematic comparison for nucleus-nucleus collisions, proton-nucleus studies will provide critical information on the parton distribution functions in nuclei, which determine the initial conditions achievable at RHIC. Lastly, machine development time is needed to reach the design luminosity and energy, establish running conditions with different beam combinations, collide polarized protons, and commission proton-nucleus collisions. Adding this to the various runs described above indicates that 37 weeks per year of RHIC operations over the coming 5 years will be just adequate for achieving the basic physics for which RHIC was built.

Theory

While the general structure of QCD is now firmly established, its properties have not yet been fully understood. Many fundamental problems are still unsolved, and are at the forefront of modern theoretical physics. One of the most important tools for making progress is lattice gauge theory, which allows one to solve complex non-linear field theory problems using a computer. These are some of the most complex problems in computer science and require enormous computing power. New capabilities will be needed in order to make progress, both in terms of interpreting experimental results and fundamental theoretical understanding.

Years 5-10

The discovery of the Quark Gluon Plasma would only be the opening chapter in the story. Many advances must be made both theoretically and experimentally in order to exhaust the complexities of this system. Improvements will be required in experiments and accelerators. Large new computers will be needed for future lattice gauge calculations as well as other computer intensive tasks. In addition, the CERN heavy ion program will be starting at the LHC. It will be a wise to make a modest investment of manpower and money so that some US participation can be possible.

For the second five-year period, we must implement significant upgrades of the collider and experiments. Such an upgrade program to increase luminosity and add new capabilities to the experiments will allow in-depth pursuit of the most promising observables characterizing the deconfined state. Following the results of the R&D, a detailed plan and schedule can be made. A gradual start of construction funding would be anticipated around 2004/5. In the mean time R&D must begin to develop the technology for these upgrades

A strong physics case for the detector enhancements can be made now and is detailed below. The original suite of detectors omitted some much needed capabilities due to limitations on the technology available at the time of their design. It has since become clear how to achieve these capabilities in the real conditions at RHIC. Together with a luminosity upgrade to the machine, moderate scale upgrades to the large detectors and/or new or reconfigured small experiments would provide the following enhanced capabilities:

- A measurement of the thermal photon and di-electron continuum at low masses and momenta yielding a spectrum for the back-body radiation characteristic of the temperature
- A significant sample of high pt hadrons in coincidence with a direct photon. The direct photon would give a direct measure of the initial momentum of the jet before energy loss.
- Direct measurement of the gluon content in the hot, dense medium (via heavy mesons formed by gluon fusion)
- Several kinds of control measurements to understand J/ψ suppression (observation of the small b-bar bound state, Υ(1S), measurement of open charm distributions, and increased overlap in observations by the various experiments). Measurements of the all the members of the Υ family (giving an indirect measurement of the χ_b via decays to the Υ) will give a direct measurement of the energy density.
- High statistics measurement of ΔG (aided by large coverage calorimetry to allow reconstruction of parton kinematics)

The Physics

The 10-15 year plan outlined above will give physicists an unprecedented chance to make specific measurements as they attempt to find answers to the basic questions posed at the beginning of this section. Some of these measurements have already begun, however others will require the higher statistics and more precision measurements afforded by the upgrade path outlined.

Thermalization and equilibration

In Relativistic Heavy Ion Collisions, how do the created systems evolve? Does the matter approach thermal equilibrium? What are the initial temperatures achieved?

The system that physicists are able to study in the laboratory is that of highly compressed nuclear matter which expands at a rapid rate, much like to early universe shortly after the Big Bang. Many of the early questions answered by experimenters will have to do with the properties of the system created at RHIC. Some of the parameters which will be crucial to understand are - the degree if thermalization, the initial temperature or energy density, the rate of expansion, and the net baryon density. Experiments probe these questions via measurement of hadrons - single particle distributions and correlations among particles, and by detecting penetrating probes, which interact only electromagnetically and therefore escape the dense system relatively unperturbed. Two-particle and multi-particle correlations reflect the dynamics of the dense matter, driven by pressure and density developed early in the collision. It would be of great interest to determine the equation of state of the hot vacuum experimentally. Lattice gauge theory predicts nearly zero compressibility for an extended range of energy densities as matter is converted into the new phase, whereas once fully converted into the new phase the compressibility should jump to the plasma value of 1/3. A latent heat is expected to accompany this transition and has significant astrophysical implications. It is an important goal of the next few years to establish a better connection between modeling of the collisions and the measurements. Measurement of collective dynamics via multi-particle correlations, such as used in flow analyses, can yield information on the pressure achieved and thereby the compressibility. Thermal radiation of photons or dileptons reflects the temperature history of the system.

Extensive study of heavy ion collisions at lower energy at the BNL AGS and CERN SPS have shown that the analysis of the distributions and correlations of soft hadrons yield the temperature and dynamics at the time the hadrons cease to interact, or “freeze out”. The space-time evolution thus measured is crucial to understanding the collision dynamics and to lending confidence in back-extrapolations to the early, hottest, phase of the collision. Systematic study of the conditions under which the hadrons freeze out, as a function of initial temperature and collision volume, will help to understand the underlying dynamics and sort out signatures of new physics from the underlying hadronic processes.

Momentum and flavor distributions of the hadrons provide information on the degree of thermal and chemical equilibration when the colliding system becomes dilute enough that hadronic strong interactions cease. Combined with information from the medium probes and thermal radiation, the space-time evolution of the entire collision can be inferred. An important goal at RHIC is to determine whether equilibration occurs early in the collision, or only later, in the cooler hadronic phase. Combining hadronic observables with collective behavior reflecting early conditions, and thermal emission of virtual and real photons are possible with the suite of experiments at RHIC.

As mentioned previously, early results from RHIC on some of these topics have already been published which indicate that the system freezes out at a lower baryon density and somewhat higher temperature than at the SPS or AGS (figure 2). This is to be expected since the freeze out temperature is a characteristic of QCD and not of particular system which is being studied. Also as mentioned previously, flow measurements indicate that the degree of thermalization is high, hence the concepts of temperature and pressure have meaning in the system under study. More information will be coming as physicists refine their measurements.

Real and virtual photons from quark-anti-quark annihilation, materializing as electron or muon pairs are radiated from the hot, dense QCD matter. While such radiation is emitted at all times during the collision, the reaction dynamics favors emission from the hottest part of the colliding system. Thus, measurement of the distribution of the blackbody thermal radiation will yield the initial temperature. The background to such a signal is formidable since photons and electrons are copiously produced from other sources such as π^0 decay. Special detectors designed to reject such backgrounds will be necessary.

PHENIX in particular has plans to add such a detector. Systematic analysis, and variation of the initial conditions will be required to nail down the interpretation.

Deconfinement

Can we locate signatures of the deconfinement phase transition as the hot matter cools? What is the origin of confinement?

The fundamental degrees of freedom in QCD are quarks and gluons. However, free quarks and gluons have never been observed, and the physical spectrum of particles contains only “hadrons”—color singlet bound states of quarks, antiquarks, and gluons. This property of QCD has been named “confinement”; the origin of this phenomenon is linked to the properties of the vacuum. Heavy ion collisions create a hot and dense environment in which the vacuum structure can “melt”, leading to novel forms of QCD matter where quarks and gluons are no longer confined. This kind of behavior has been confirmed by numerical calculations on the space-time lattice. Further progress in the theory is imperative, and includes both new analytical methods and large—scale numerical simulations on the lattice. New lattice methods and more powerful computers would enable a breakthrough in the understanding of confinement. To investigate the consequences of deconfinement phase transitions for the experimental observables in heavy ion collisions, we will need the development of QCD based event generators and the facilities for large-scale numerical simulations.

Probes of the deconfined state of matter include hard scattering processes, J/ψ suppression, and possibly strangeness production. Hard scattering processes take place in collisions between quarks or gluons (partons) in the initial state, before any thermalization can take place or quark-gluon plasma can be formed. In vacuum, hard scatterings produce either jets of particles with high transverse momenta or heavy quarks like charm or bottom, of which a small fraction materialize in bound $c\bar{c}$ (J/ψ, χ_c) or $b\bar{b}$ (Υ, χ_b) states. Since the initially scattered partons must traverse the full space-time evolution of the reaction, they can serve as probes of the dense QCD matter. In particular, their energy as they traverse the dense matter yields information about the medium. As jet production can be calculated quantitatively with perturbative QCD, the observed abundance and properties of high-p_t hadrons and heavy flavors will reflect the dense matter they encounter.

Measurement of the hard scattering processes via high p_t hadrons and heavy flavor distributions will indicate to what extent the fast particles lose energy in the dense medium. This energy loss results in energy transfer from fast particles to the medium and drives thermalization. Furthermore, this energy transfer multiplies the number of gluons and therefore drives particle production, increasing the density of the medium further. In fact, some theoretical predictions indicate that matter may reach the stage of gluon saturation – in such a case the physics is determined by interactions in a dense gluon gas, calculable using perturbative QCD, with subsequent hydrodynamic expansion. Measured particle yields, spectra and correlations to transverse momenta of at least 10 GeV/c p_t are needed to see whether such predictions are correct. Presumably, particles with extremely high momenta will never thermalize, providing a built-in control measurement; the hadron p_t spectra and correlations among fast hadrons will indicate at which point this becomes true. As mentioned, Phenix may have already seen hints of this phenomenon in the π^0 pt spectra. Further measurements will be made in the second year of data taking, giving the possibility of measuring the spectrum to a pt of 10 GeV. In addition, important comparison data will be taken in the coming years in pp and pA collisions.

In the future when a significant luminosity upgrade is available, measurements of direct photons produced opposite high pt hadrons can be made. Since the photon recoils against the quark jet, and since it does not suffer energy loss in the deconfined medium, the photon serves as a indicator of the initial transverse momentum of the jet. This will provide a means to make a careful quantitative measure of the energy loss. One interesting possibility is to flavor tag the high pt hadron. A leading K^- with no valence quarks is more likely to come from a gluon jet. This would allow one to measure the difference in the energy loss between gluon and quark jets. Gluon jets are expected to loose energy at twice the rate of quark jets in a deconfined medium.

J/ψ suppression is another well known signature of deconfinement. PHENIX will be able to measure J/ψ production in both the muon and electron channels. STAR will have access to the electron channel within the next several years as their electromagnetic calorimeter is completed providing a second measurement of this signature. This is a critical check between experiments which was not done in the CERN experiments. One of the critical measurements which must accompany the measurement of the J/ψ is that of open charm production. To do this, specialized vertex detectors must be added with the position resolution which would allow a measurement of the charm vertex separated from the original event vertex. STAR, PHOBOS and PHENIX have all embarked on R and D programs to construct such an upgrade.

The J/ψ is but one of the vector mesons in the charm family. The excited states of the J/ψ as well as the Υ family will all exhibit some degree of suppression. The suppression of the associated states, χ_c and χ_b can also be observed since they decay to the vector mesons. Each of these states will "melt" at a different temperature. In fact the Υ will be used as a control since its should not be suppressed at all at RHIC energies. By varying the temperature of the system though changes in beam energy one can change the pattern of suppression of the various states. Not only would this be a convincing signature of a phase transition, it would give a good measure of the actual energy density. This will require the major upgrade in luminosity available in RHIC 2.

While the production of strangeness particles tells us about thermalization, it may also be an indicator of deconfinement. It is well established experimentally that strangeness is enhanced in relativistic heavy ion collisions. If this enhancement occurs while the medium is in a deconfined state, multi-strange particles should be exhibit an even stronger enhancement relative to pp or pA collisions, simply from combinatoric arguments. The interpretation of such signatures, however has always been somewhat problematic and will need to be corroborated with other evidence.

Chiral Symmetry Restoration/Vacuum/Mass

What are the properties of QCD vacuum? What is the origin of chiral symmetry breaking and what it its connection to the masses of the hadrons?

Chiral symmetry is the symmetry between "left" and "right" handed objects and has to do with whether the direction of spin is clockwise or counter-clockwise. Chiral symmetry is broken through the creation of a vacuum scalar condensate that couples to baryons and provides most of the mass for hadrons. The challenge for RHIC measurements is to search for evidence of in-medium mass changes of the low mass vector mesons associated with the restoration of chiral symmetry. A direct measurement of the mass of light vector mesons such as the ρ,ω, and ϕ is possible since they decay rather rapidly within the fireball created at the time of collisions and before hadronization.. The decay to di-electrons is particularly interesting since electrons should not be rescattered in the medium and their invariant mass should reflect the mass of the vector meson in the altered vacuum state. Since some fraction of the vector mesons decay outside the medium (in the case of the ω some 20-30% decay inside the medium), these can be used as a calibration point for the measurement. The fraction exhibiting a shifted mass should change as a function of the transverse momentum and the size of the central fireball. This would be a particularly dramatic signature of the altered vacuum.
As in the case of the thermal di-electron signal, a major upgrade will be needed to reject the background for detection of the ρ, the shortest lived, and hence the broadest of the vector mesons. Observation of the ρ will be important, since they decay entirely within the fireball and its spectrum may be able to give us a thermal history of the evolution of the system.

The presence of a phase transition as the system created in a RHIC collision cools is expected to cause fluctuations, which may perhaps survive the hadronic phase as fluctuations in particle number and type. Fluctuations and droplet formation are of particular interest, since a similar process may account for much of the large scale structure of the universe and the inhomogeneities observed in the cosmic microwave background. A variety of fluctuations have been proposed as a signature of a phase transition. If the transition is first order, the growth of hadronic droplets and the shrinking of quark-gluon droplets may yield a lumpy final state and large fluctuations in particle number as a function of rapidity. If the transition is a smooth but sufficiently rapid crossover, domains of misaligned chiral condensate may be excited. If the transition occurs near a critical point separating first order behavior from crossover behavior, long wavelength fluctuations imprint unique signatures on the momenta of soft pions. Experiments will search for such phenomena, and correlate their appearance with other quark-gluon plasma signatures.

The theory of chiral symmetry breaking and restoration is under active development. In hot and dense matter produced in relativistic heavy ion collisions, the chiral symmetry can be restored. Further theoretical progress is needed to understand the microscopic origin of chiral symmetry breaking and the mechanism of its restoration. It will include development of new analytical tools, and further progress in lattice calculations. In order to investigate chiral symmetry on the lattice, one has to be able to perform calculations with realistically small masses of quarks. This places severe constraints on the size of the lattice, and requires new methods (e.g., “domain wall fermions”), and new and more powerful computers.

The Strong CP problem

While QCD allows for a violation of parity and charge conjugation combined with parity (CP), this violation has been never observed experimentally in normal conditions. Why this is so is still a subject of theoretical studies. It would be of great interest to check if CP violating processes are possible under extreme conditions of high temperature and density. Theoretical progress here is linked to the understanding of topological effects in gauge theories at zero and finite temperatures. This requires both analytical tools and lattice simulations. To search for the effects of anomalous parity and CP violation in experiment, one needs to incorporate these processes into the event generators.

Clever experimental signature for CP violating bulk phenomena in heavy ion collisions at RHIC have been devised. In theory since CP is conserved in ordinary strong interactions, the signature of the altered CP state should shine pass through the hadronic debris.

High Density Matter

What are the properties of matter at the highest energy densities? Is the basic idea that this is best described using fundamental quarks and gluons correct?

Gluonic interactions may be expected to dominate the first few fm/c of the collisions, immediately following the initial nucleon-nucleon interactions as the nuclei penetrate one another. Gluon fusion processes dominate the production of charm and bottom quarks, as well as drive W production at energies attainable at RHIC. Consequently, measurements of open charm and bottom decays will likely be the most important ways to study the gluon fields inside heavy nuclei and their excitations in heavy ion collisions. The Drell-Yan process of quark-antiquark annihilation probes the quark structure functions. Achieving adequate luminosity and detector acceptance to measure this at RHIC will be an invaluable tool to study the evolution of the quark structure functions to small-x inside heavy nuclei (measurements of p-nucleus collisions will yield this information) and as the parton distributions evolve during a heavy ion collision.

The nuclear shadowing will be measured directly via Drell-Yan and other hard processes in proton-nucleus collisions. Experiments must measure, with sufficient statistics, the dimuon distributions at high mass and hadron spectra at high pt (at or above 10 GeV/c) to determine the extent of shadowing in kinematic regions accessible at RHIC. The answers feed back, of course, into understanding the initial conditions in nucleus-nucleus collisions. However, they also probe the gluon field properties directly. If the gluon and quark densities can saturate, this will affect the gluon distribution deep inside a heavy nucleus as well as the dynamics of the early stage of a heavy ion collision. Measuring the intrinsic kt via hard probes, and observing how this depends on x as well as the volume of the dense matter produced in heavy ion collisions can address these questions. Such measurements will require increased luminosity of RHIC for sufficient yields. They will also require upgrades of the detectors for efficient reconstruction of the hard probes.

The behavior of QCD at the high-energy frontier has not yet been understood. The most simple, and most fundamental, questions are still unanswered: Why do hadron cross-sections rise? How are particles produced? What is the wave function of a high-energy hadron? RHIC will help to find the answers by providing detailed data on particle production in a wide range of atomic numbers and energies. Progress in the understanding high-energy behavior in QCD will allow us to reconstruct initial conditions in heavy ion collisions, which is a crucial prerequisite for theoretical description of the entire process. It will need further development of new theoretical tools, where there has been a remarkable recent progress. It will also need large-scale real-time Monte Carlo numerical simulations.

Correlating the signatures

Phase transitions occur at a particular energy density. It is crucial to cross correlate the conditions under which the signals appear in order to rule out proposed hadronic explanations and prove that new physics is the ONLY consistent explanation. This necessitates experiments measuring multiple signatures, sufficient statistics and good systematic understanding of even the rarest ones, and good cross checking of event classes across different experiments.

Finally, it is crucial that adequate data be taken looking for these same observables in pp collusions or proton nucleas collusions in which a phase transition is not expected to occur to provide a baseline for the nucleus-nucleus measurements.

Detector Upgrade Plans

In order to carry out the physics goals for years 5-10 a luminosity increase to RHIC will be required. To handle the higher data rates, and to enhance physics capabilities the two large detectors, STAR and PHENIX, will require major upgrades. An R&D program during the early phase of RHIC operations is crucial in order to design, test and prototype new detectors systems for this upgrade. The additional physics goals will also require an upgrade of the RHIC Computing Facility to be able to handle the increase in data volume, and demands for computing power for reconstruction and analysis.

The major upgrade to STAR will require replacement of the time projection chamber(TPC) with a fast tracking device capable of particle identification. It is also anticipated that there will be extended coverage. Detailed study is needed for the design of this new system.

PHENIX will be adding precision 2p vertex tracking for the detection of decay vertices from charmed particles, capabilities to reject electron background from daltiz decays and photon conversion, and for the spin program, additional tracking and calorimetry with larger acceptance over the full azimuth.

Both detectors will require a significant improvement in data acquisition rate and trigger capabilities. In addition, both detectors are pursuing similar technologies in tracking, particle identification and vertex detection. Joint R&D efforts are underway between the two collaborations.

These upgrades should yield two detectors capable of handling the full suite of physics measurements possible at RHIC, not only in nucleus-nucleus collisions, but in proton-nucleus, proton-proton, and spin dependent proton collisions as well. In addition, the capabilities of the two detectors will be well matched to one another so that there is a good balance between complementarity in being able to explore different kinds of measurements, and similarity so that critical results can be verified by detectors with different systematic uncertainties.

Heavy ions in the LHC, and U.S. participation in the program

In 2006 the construction of a new collider, with even higher energy capabilities than RHIC will be completed in Europe. It is the so-called Large Hadron Collider or LHC currently under construction at CERN. LHC is being built primarily for pp studies, however there are plans to also use it for heavy ion studies. When used as a heavy ion collider, LHC will be able to operate at center of mass energy of about 30 times that of RHIC. It will thus open up the opportunity to probe hadronic matter at temperatures well above the QGP phase transition. At the time of completion of LHC, the heavy ion community will have at its disposal two complementary first-rate tools, RHIC and LHC. Although the focus of the US heavy ion community should be and must be RHIC, it is important for us to be able to contribute to and to influence physics at the higher energy domain of LHC. Historical experience teaches us that a large increase in available energy usually leads to surprises, and that there may be a need to study at a higher energy intriguing results observed at a lower energy.

A moderate involvement of the US at LHC, of about $10M in equipment funding over 3-4 years and commitment of about 50 US scientists (10% of the involvement in RHIC experiments), will have a significant impact on both the LHC and on the US heavy ion community. This will continue a long-standing, mutually beneficial tradition in our field for US and European scientists to participate in each other's research endeavors.

In relativistic heavy ion collisions at the LHC, the apparent density of low-x virtual gluons in the colliding nuclei will be effectively at saturation; the incoming nuclei will act as densely packed "gluon walls" approaching each other at the speed of light. Such saturated gluon fields have the important property that they can be calculated using classical chromodynamics. It is expected that, compared to RHIC, the lifetime of the quark-gluon plasma state will be longer by an order of magnitude. The fireballs created at LHC will spend almost all of their lifetime in a purely partonic state. For the first time conditions will be such that the dominating aspects of the initial state can be described without resorting to phenomenological “soft” hadronic physics. Its low net baryon density will also get one significantly closer to the conditions of the hot matter from which the early universe was made during its first few microseconds.

The higher initial energy will result in the formation of more “hard probes” like jets or U at significantly higher rates and easier to detect and analyze. The combination of more probes and a larger fireball opens widely the time window available for experimentally probing the quark-gluon plasma state. Furthermore the higher energy scale makes the relevant perturbative QCD calculations more reliable. Combined pp and pA with AA measurements will provide information on the spatial distribution of shadowing at very low x, in addition to the standard “unshadowed” structure functions needed for the calibration of AA results. Larger production yields of final state particles will allow first precise event-by-event and correlation analyses.

LHC is a collider that will be able to accelerate protons up to 7TeV and several species of nuclei as heavy as lead up to 7 TeV/charge. It is scheduled to be completed late in 2006 and it is planned to operate it as a heavy ion collider one month per year. The US high-energy community has a major involvement in the project. It is presently investing $440M into the construction of the collider and its experiments. Four large detectors are under construction. One of them, ALICE, is a dedicated heavy ion experiment. Another, CMS, has incorporated heavy ion studies as an integral part of their scientific program. Atlas is now contemplating a program in heavy ions as well. Although the detector designs are well advanced, significant opportunities exist to have a major impact on both the detectors themselves and preparations for data analysis.

Blue Pages

1) **Phase diagram**
2) **Vacuum**
3) **Mass shift of light vector mesons**
4) **J/y suppression**

Figure Captions

1) **Phase diagram**

The QCD phase diagram showing temperature on the abscissa, and baryon density on the ordinate. …

2) **Redlich with RHIC on it**
3) **The 4 RHIC detectors**

STAR is a large acceptance detector built around a central Time Projection Chamber (TPC) in a solenoidal magnetic field. Inside the TPC is a silicon vertex tracker (SVT) for detecting secondary vertices. An electromagnetic calorimeter (EMCAL) and forward TPC’s are being installed in the next few years. A small acceptance RICH detector for high momentum particle ID will be replaced in the next several years by a TOF system.

The PHENIX detector is composed of 4 spectrometers optimized for detecting and identifying electrons, muons, photons and hadrons. Multiple detector subsystems are used in the two central arms, yielding good momentum resolution and particle identification. Of particular note is redundancy in electron identification capabilities, giving a total e/π rejection of better than 10^{-4}. Excellent hadron identification via Time Of Flight (TOF) is available over a small angular range. Muons are detected in two arms covering forward and backward rapidities, where the muons have a kinematic boost enabling them to be separated from the copious hadrons produced in the collisions.

PHOBOS, one of the two smaller detectors, is primarily composed of silicon and is optimized for large event rates. It consists of a central two-arm spectrometer, allowing for measurements at very low-pt, and a full acceptance multiplicity array. High-pt particle identification is provided by a TOF system.

BRAHMS specializes in measuring the fragmentation region of the collisions. It is composed of two spectrometers, each with a rather small aperture, which rotate thereby allowing the detector to cover a large rapidity region by combining data from runs with the detectors in various positions.

4) **dn/deta**
5) **star flow**
6) **pi0**

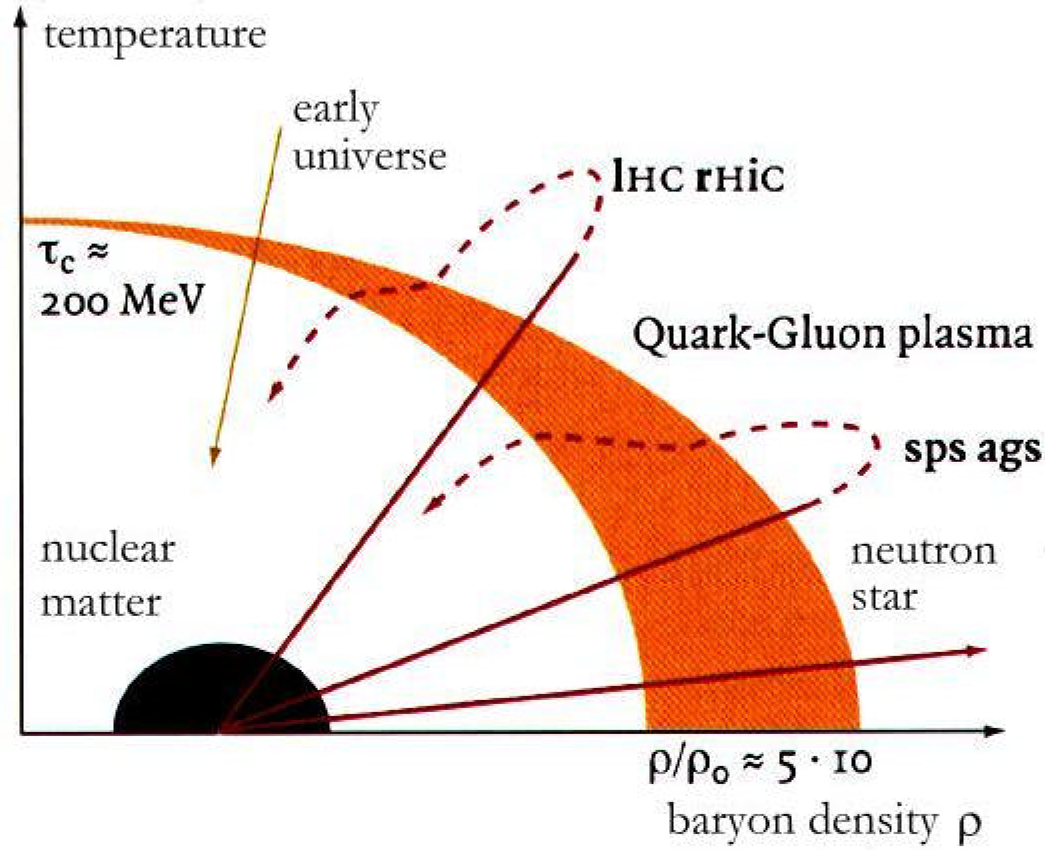
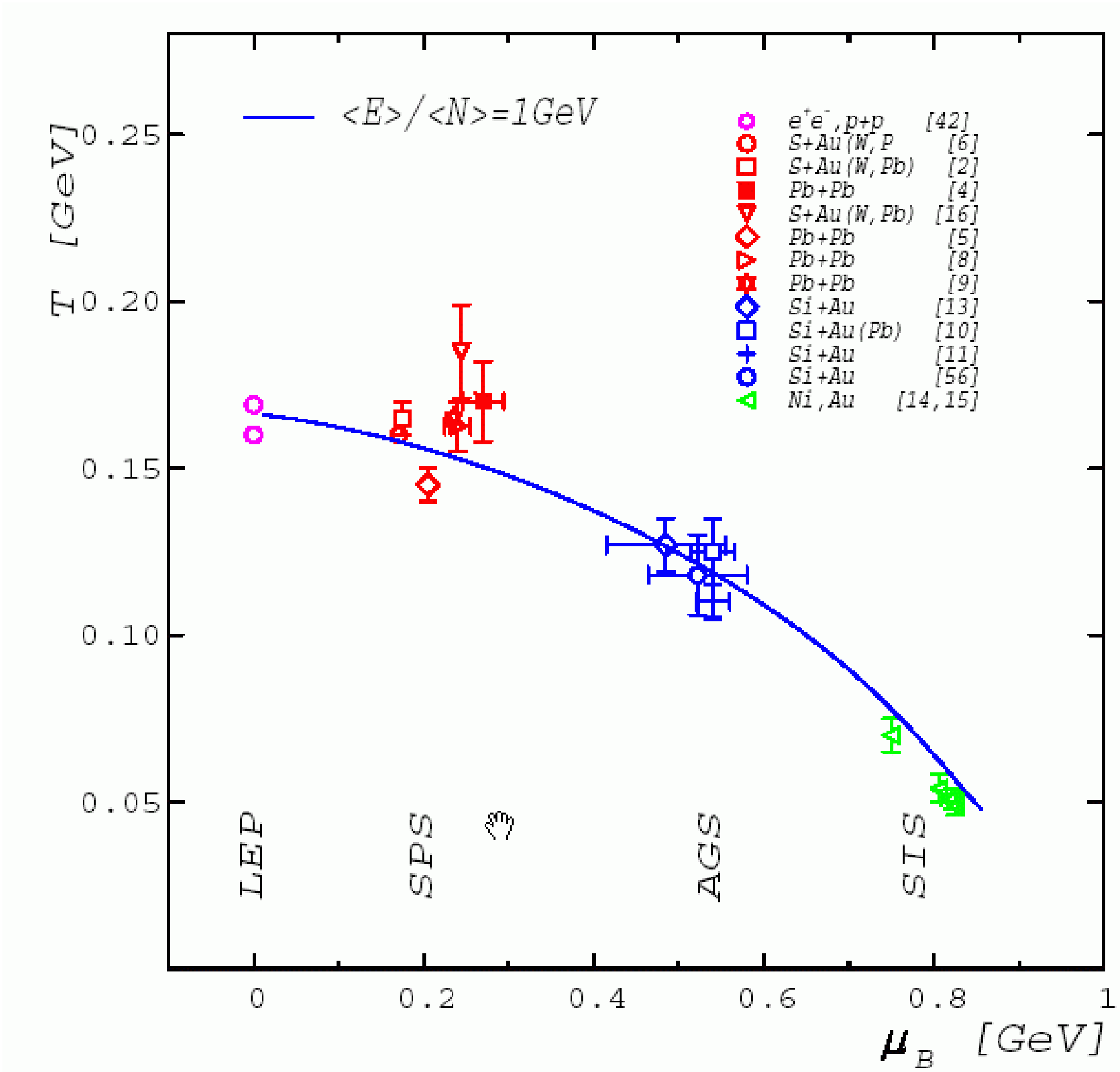
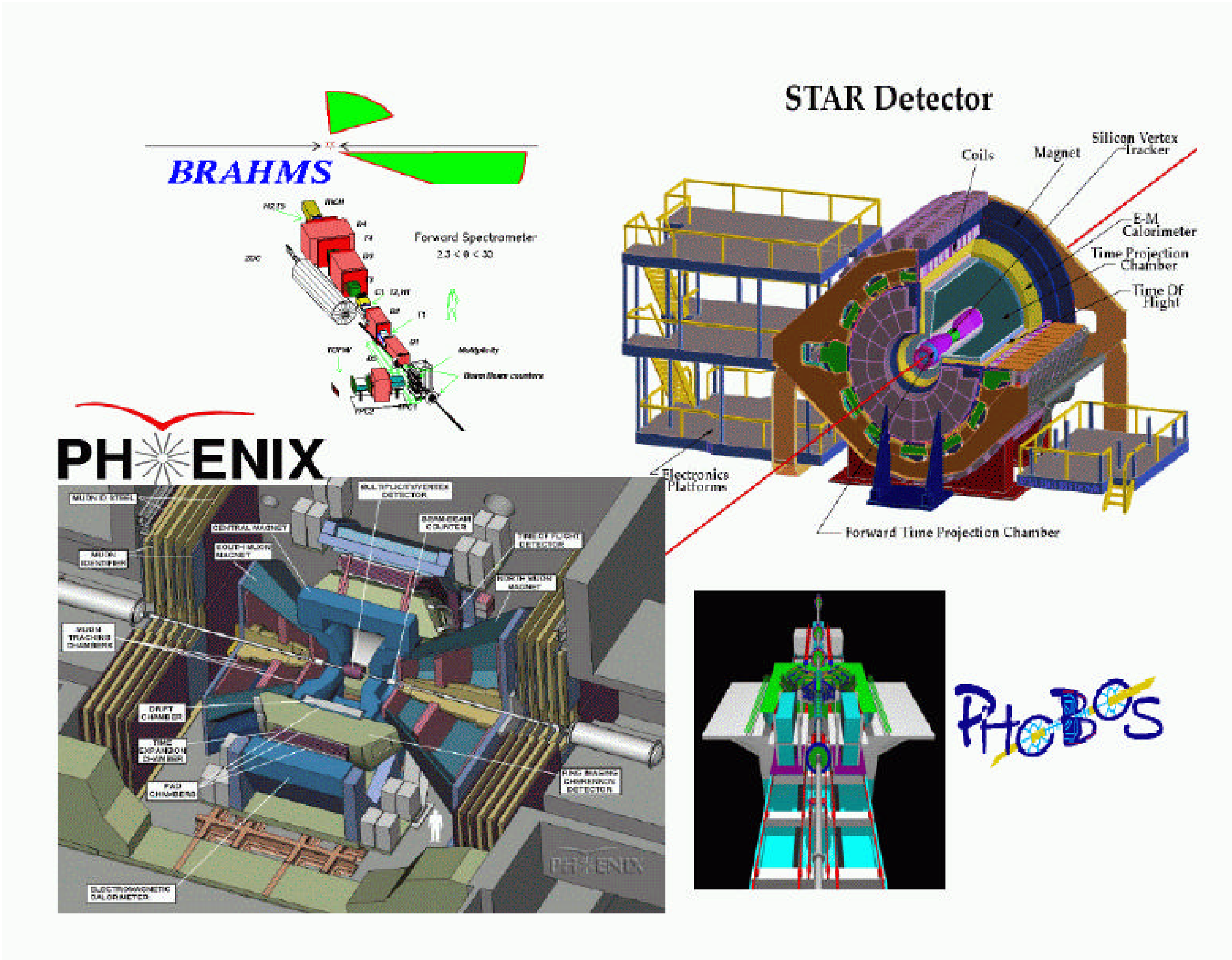

temperature
early universe
lHC rHIC
$\tau_c \approx$ 200 MeV
Quark-Gluon plasma
sps ags
nuclear matter
neutron star
$\rho/\rho_0 \approx 5 \cdot 10$
baryon density ρ

Figure 1



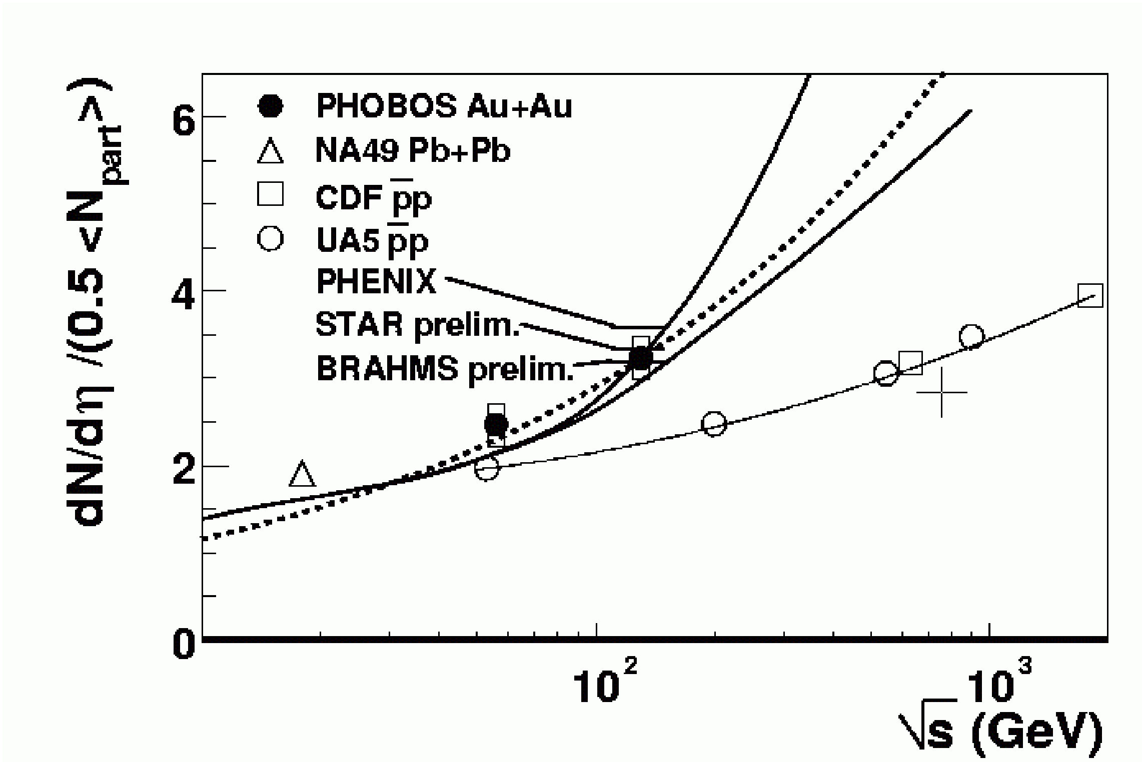
<E>/<N>=1GeV
e+e-,p+p [42]
S+Au(W,P [6]
S+Au(W,Pb) [2]
Pb+Pb [4]
S+Au(W,Pb) [16]
Pb+Pb [5]
Pb+Pb [8]
Pb+Pb [9]
Si+Au [13]
Si+Au(Pb) [10]
Si+Au [11]
Si+Au [56]
Ni,Au [14,15]
LEP
SPS
AGS
SIS
T [GeV]
0.25
0.20
0.15
0.10
0.05
0
0.2
0.4
0.6
0.8
1
μB [GeV]

Figure 2



BRAHMS
Forward Spectrometer
STAR Detector
Coils
Magnet
Silicon Vertex Tracker
E-M Calorimeter
Time Projection Chamber
Time Of Flight
Electronics Platforms
Forward Time Projection Chamber
PHENIX
PHOBOS

Figure 3



PHOBOS Au+Au
NA49 Pb+Pb
CDF $\bar{p}p$
UA5 $\bar{p}p$
PHENIX
STAR prelim.
BRAHMS prelim.
$dN/d\eta\ /(0.5\ \langle N_{part} \rangle)$
0
2
4
6
10^2
10^3
$\sqrt{s}$ (GeV)

Figure 4

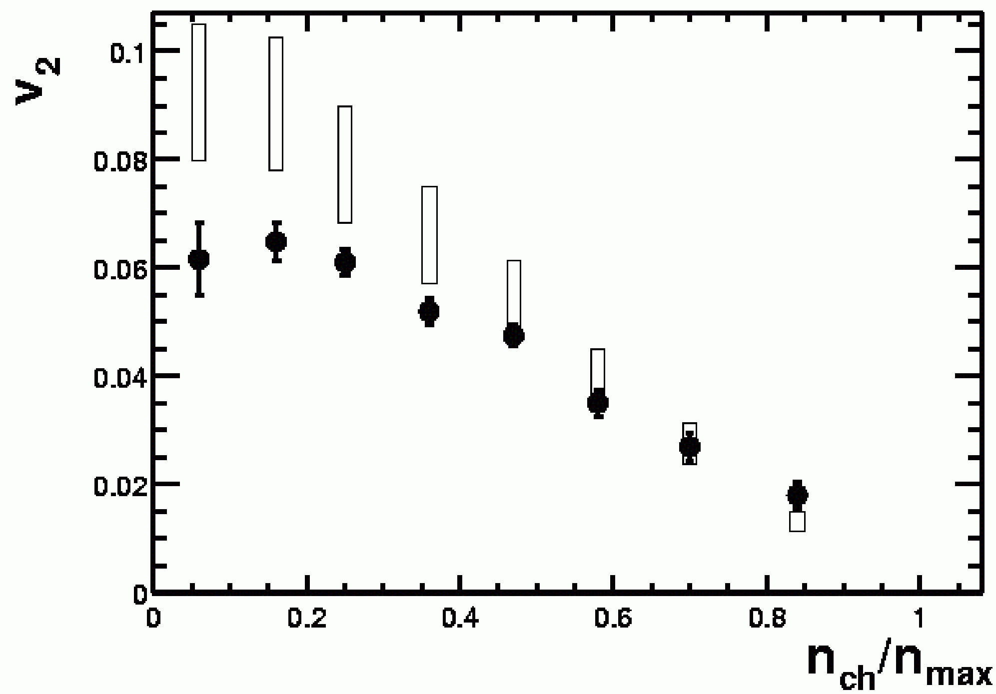
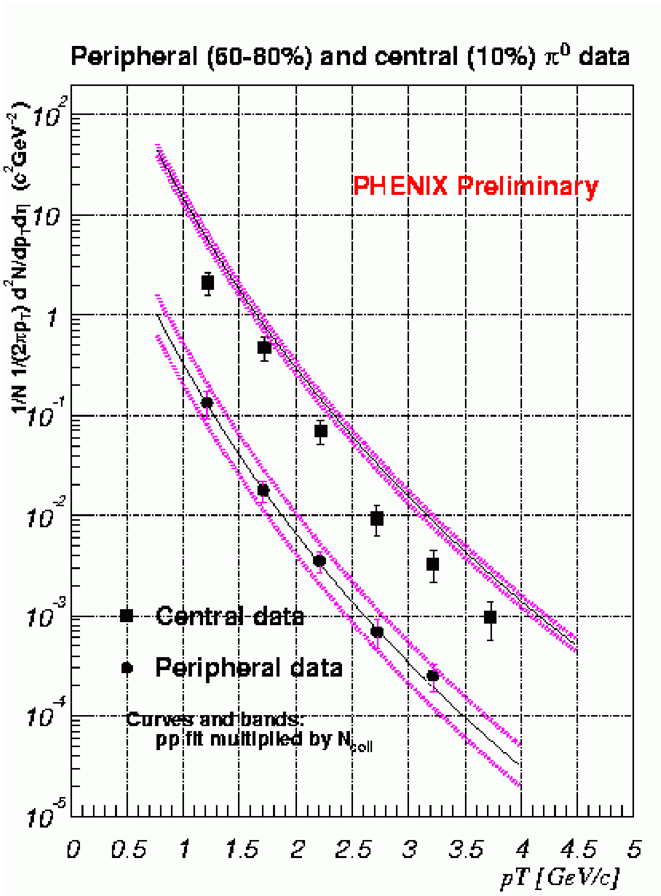
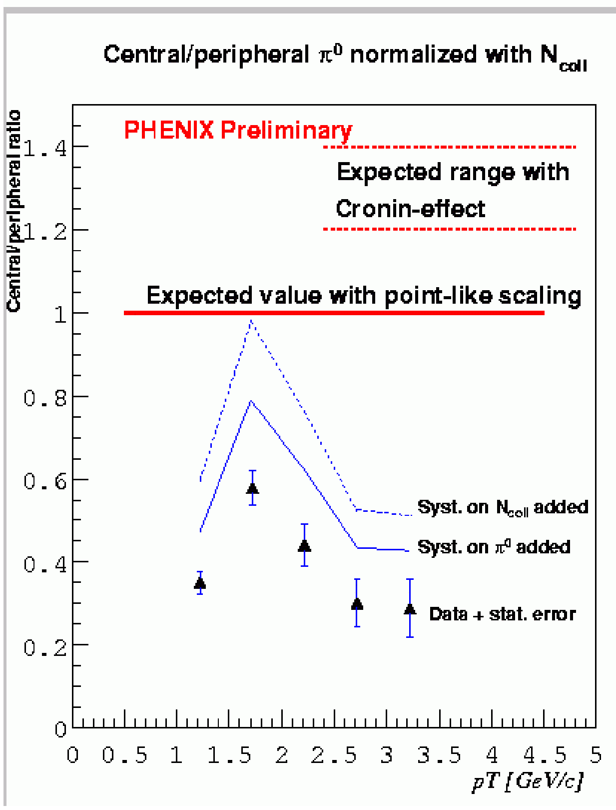


FIG. 3. Elliptic flow (solid points) as a function of centrality defined as n_{ch}/n_{max}. The open rectangles show a range of values expected for v_2 in the hydrodynamic limit, scaled from ϵ, the initial space eccentricity of the overlap region. The lower edges correspond to ϵ multiplied by 0.19 and the upper edges to ϵ multiplied by 0.25.

Figure 5


Peripheral (60-80%) and central (10%) π^0 data
PHENIX Preliminary
1/N 1/(2πp_T) d²N/dp_Tdη (c²GeV⁻²)
Central data
Peripheral data
Curves and bands:
pp fit multiplied by N_coll
pT [GeV/c]


Central/peripheral π^0 normalized with N_coll
PHENIX Preliminary
Central/peripheral ratio
Expected range with
Cronin-effect
Expected value with point-like scaling
Syst. on N_coll added
Syst. on π⁰ added
Data + stat. error
pT [GeV/c]